Division 6 - Lincoln Laboratory
Massachusetts Institute of Technology
Lexington 73, Massachusetts

SUBJECT: THOUGHTS ON INCREMENTAL PERMEABILITY

To: Group 63

From: John B. Goodenough

Date: September 17, 1954

Abstract: After a short discussion of the factors which influence the incremental permeability, three different methods are discussed which should give a large change in incremental permeability with a change of the biasing field. The first requires a grain-oriented magnetic tape and takes advantage of demagnetizing fields. The second requires a material with a square B-H loop, a low coercive force, and a large maximum permeability. The third requires a material with low crystalline anisotropy. Finally some currently available materials are suggested.

I. INTRODUCTION

When a magnetic field acting on a specimen is maintained constant and an additional field is alternated cyclically between two limiting values, the fields and inductions thus produced are said to be superposed. The incremental permeability μ_Δ is defined as the cyclically changing induction ΔB divided by the cyclically changing field strength ΔH. On a B-H plot, the point midway between the tips of the superposed a-c loop is designated H_b, B_b ; these quantities are called the biasing field strength and the biasing induction respectively. As a result of a talk with Peter H. Haas of the Diamond Ordnance Fuze Laboratories, Washington, D.C., it has been learned that there is considerable interest in obtaining a material which has a large value of $\Delta\mu_\Delta/\Delta H_b$, where $\Delta\mu_\Delta$ is the change in the incremental permeability when the d-c biasing field is changed by ΔH_b.

Before an intelligent search for a suitable material can be made, it is necessary to understand the mechanisms which contribute to the incremental permeability and how these mechanisms can be most effectively exploited. In Section II there is a discussion of those mechanisms which contribute most strongly to the incremental permeability. In Section III there follows a discussion of some optimum B-H loop shapes and biasing points for $\Delta\mu_\Delta/\Delta H_o$ to be a maximum. In Section IV there are some concluding remarks with regard to currently available materials.

II. MECHANISMS

The permeability μ is a measure of the change of induction through a magnetic specimen as a function of an externally applied field H. It is itself a function of H and of the magnetic history of the specimen. There are two principal factors which determine the magnitude of the permeability, an external-field-induced rotation of the elementary magnetic moments and domain-wall motion.

A. Field-Induced Rotation

When an external field $\underline{H}$ is applied to a specimen, the individual atomic moments $\underline{m}$ are subject to a torque $\underline{m} \times \underline{H}$. The atomic moments rotate in the direction of the applied field against the crystalline anisotropy forces. Below saturation the crystalline forces are of sufficient strength to prevent complete alignment of the atomic moments in the direction of the externally applied field. The significance for μ_Δ of the relation torque = $\underline{m} \times \underline{H}$ can be qualitatively summarized by the two following statements.

1.) Although the initial torque on two antiparallel moments of the same magnitude is identical, the moment which has a component antiparallel to an applied field H will suffer the greater rotation. However, in an a-c field this difference in rotation is averaged out. Therefore there can be no change in the rotational contribution to the incremental permeability by a change of induction which is due to 180°-wall motion.

2.) If two atomic moments of equal amplitude are mutually perpendicular, the moment with the smaller component along the axis of the applied-field direction will suffer the larger rotation provided the external field is not strong enough to cause a moment to overcome the crystalline anisotropy forces associated with its original crystalline orientation. This difference in rotation is greater the more nearly perpendicular to the applied field is one of the moments.

It follows that the rotational contribution to an incremental permeability will be larger for a specimen which has its elementary magnetic moments more nearly perpendicular to the direction of the a-c field. Therefore if it is possible, by a small ΔH_b to change the direction of the atomic moments from a parallel to a perpendicular alignment with the a-c field, the rotational contribution to $\Delta \mu_\Delta / \Delta H_b$ can be made relatively large. A possible scheme which could take advantage of this phenomenon is suggested in Section III A.

If the crystalline anisotropy is so small that the domain wall is too broad for physical significance, the atomic moments can be rotated readily by small external fields, but they will be little affected by small fields which are superimposed on a large biasing field.

In Section IIIC there is a discussion of low-anisotropy materials.

B. Domain-Wall Motion

The motion of a domain wall, especially of a 180° domain wall, will change, or reverse, the direction of magnetization within the volume it sweeps out. If this volume is large for a given ΔH, the incremental permeability will be large. It immediately follows that the incremental permeability will vary both as the area of domain wall which is present in the material and the distance the walls can move under the influence of the a-c field ΔH. The distance the walls can move will depend upon the depth of the potential wells in which they are located and the distance between potential barriers to wall movement. The coercivity is a measure of the depth of the potential wells, and the maximum permeability is a measure of the maximum distance between potential barriers. To obtain a large domain-wall contribution to μ_Δ, it is necessary to have a large area of domain wall present, a low coercive force, and a large maximum permeability. To obtain a large $\Delta\mu_\Delta$ in a small ΔH_b, it is necessary to eliminate a large amount of wall area in the interval ΔH_b. The type of material which can exploit these features is discussed in Section IIIB.

III. POSSIBLE OPERATIONAL SCHEMES

A. Thin Sheet of Grain-Oriented Metal

A possible method of expoliting the rotational contribution to the incremental permeability is to take advantage of demagnetization effects. Let a thin sheet of grain-oriented, ferromagnetic metal be wound, as shown in Fig. 1, so that the a-c field is directed in the plane of the sheet parallel to its long edge. Let a large biasing field H_b also be in the same direction so that the elementary magnetic moments are in this same direction. Only at the ends of the sheet will there be closure domains in which the atomic moments are perpendicular to the a-c field.

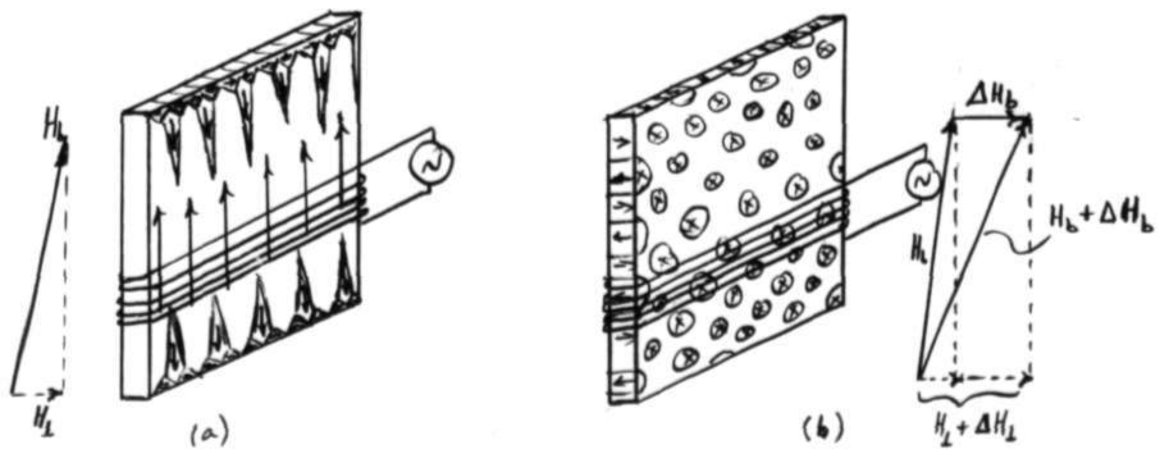

Figure 1.
Idealized domain-pattern change in a grain-oriented metal sheet due to a change in biasing field ΔH_b.

If the sheet is long compared to its width, the percentage volume of material in closure domains is extremely small. Since there are no mobile domain walls in such a domain pattern, the rotational contribution to μ_Δ predominates. But the rotational contribution is small because the atomic moments are parallel to the a-c field. If the metal sheet is so grain oriented that a direction of easy magnetization is in the direction of the a-c field, the biasing field H_b need not be too large to accomplish such a domain configuration. In this configuration, the incremental permeability μ_Δ must be small.

Now let the biasing field H_b be rotated until it is perpendicular to the metal sheet. In this instance strong demagnetizing fields will be set up so that the domain pattern is complex. The great majority of the atomic moments will, however, be perpendicular to the plane of the metal sheet and therefore perpendicular to the a-c field. Therefore the rotational contribution to μ_Δ is large so that even if the complex domain structure is immobile and there is no domain-wall contribution, there is a considerable change in μ_Δ as a result of the change in domain pattern.

If the metal sheet is sufficiently oriented that it has a square B-H loop if wrapped into a toroid, then as H_b is rotated, there is a relatively sharp transition from the domain pattern of Fig. 1(a) to that of Fig. 1 (b). If $H_\perp$ is the component of H_b which is perpendicular to the metal sheet and $B_\parallel$ is the component of the induction parallel to the a-c field, then a plot of $B_\parallel$ vs. $H_\perp$ should be as shown in Fig. 2 (a). The sharpness of the break will depend upon the degree of orientation of the metallic grains. To obtain a maximum value of $\Delta\mu_\Delta/\Delta H_b$, the biasing field should be rotated until $H_\perp = H'$, where H' is a value such as that shown in Fig. 2(a). The influence field ΔH_b should be directed perpendicular to the sheet, as shown in Fig. 1(b), so that $\Delta H_b = \Delta H_\perp$. If ΔH_b is of sufficient magnitude to cause a complete change from the domain configuration in Fig. 1(a) to that in Fig. 1(b), then $\Delta\mu_\Delta$ will be large. To make $\Delta\mu_\Delta/\Delta H_b$ large, this ΔH_b must be small, or $H_\perp' - H_\perp''$ (see Fig. 2) must be small. A plot of μ_Δ vs. $H_\perp$ is shown in Fig. 2(b). This illustrates how $(\Delta\mu_\Delta/\Delta H_b)$maximum is increased if $H_\perp'$ and $H_\perp''$ are brought close together.

If the application requires small losses, 1/4-mil sheets of metal tape will practically eliminate eddy-current losses. Several such sheets in lamellar layers should provide the necessary inductance change.

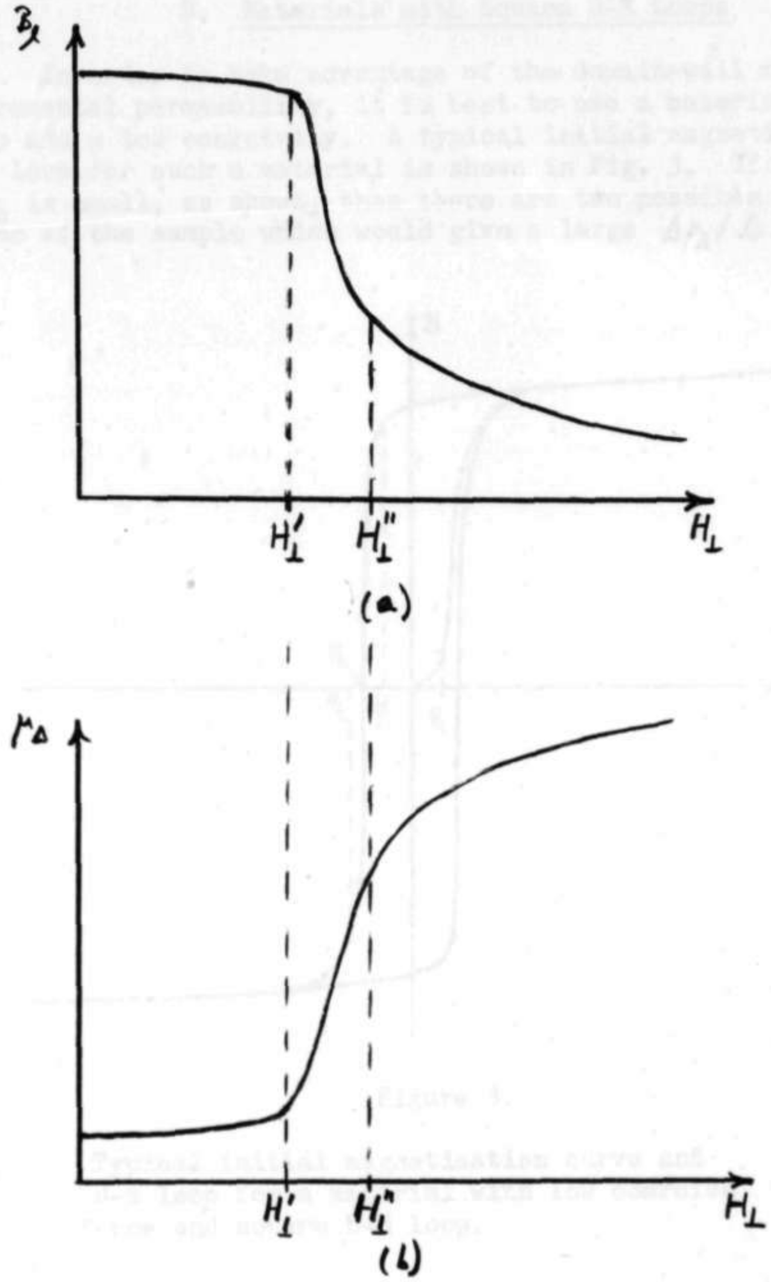

Figure 2.

(a) Component of inductance parallel to long dimension of a grain-oriented metallic-ribbon sheet and

(b) Incremental permeability as a function of the component of the external field strength perpendicular to the sheet.

B. Materials with Square B-H Loops

In order to take advantage of the domain-wall contribution to the incremental permeability, it is best to use a material with a square B-H loop and a low coercivity. A typical initial magnetization curve and B-H loop for such a material is shown in Fig. 3. If the biasing field H_b is small, as shown, then there are two possible magnetic histories of the sample which would give a large $\Delta\mu / \Delta H_b$.

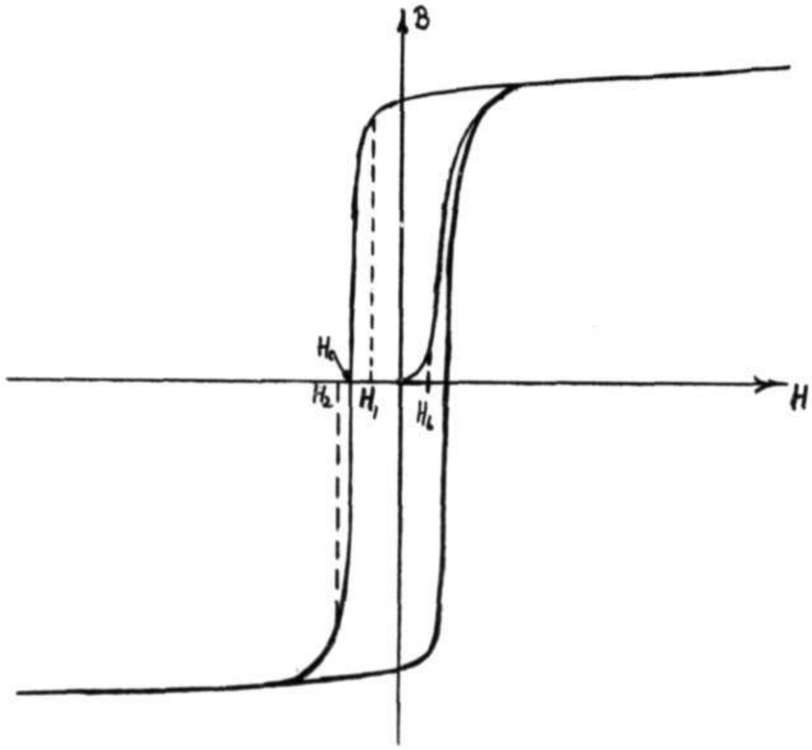

Figure 3.

Typical initial magnetization curve and B-H loop for a material with low coercive force and square B-H loop.

1.) Material Originally Demagnetized.

If the material is originally demagnetized, it contains a complex domain pattern and a large domain-wall area. If the coercive force is low, the walls are not tightly bound, and they can be moved by the small a-c field. This means the initial permeability is large. If ΔH_b is sufficiently large that $H_b + \Delta H_b > H_c$, then the domain pattern is simplified and the total wall area is much reduced after ΔH_b is applied. At the biasing field $H_b + \Delta H_b$, therefore, the domain wall-contribution to the incremental permeability is much smaller than that to the initial permeability. The rotational contribution to the permeability will also decrease from H_b to $H_b + \Delta H_b$ since whatever the volume of material with atomic moments nearly perpendicular to the a-c field at H_b, it is reduced when the domain pattern is simplified. Unless a relatively large percentage of the volume in the demagnetized state is magnetized nearly perpendicular to the a-c field, however, the rotational contribution to the change in μ_Δ will be small. Both effects complement one another to produce a marked decrease in μ_Δ after the application of ΔH_b.

2.) Material Originally at Remanence $-B_r$.

In this instance an increment in the biasing field increases μ_Δ , whereas in the former example it decreases μ_Δ. At $-B_r$ there is little, if any, domain wall present in the material if it has a square B-H loop. After an increment in the biasing field is applied such that $H_b + \Delta H_b + \frac{1}{2}\Delta H \approx H_c$, several domains of reverse magnetization will be created in the material, and in the a-c cycle the area of Bloch wall will be approximately its maximum value for this particular B-H loop. If the coercive force is small, a small ΔH can move these walls appreciably and μ_Δ is large.

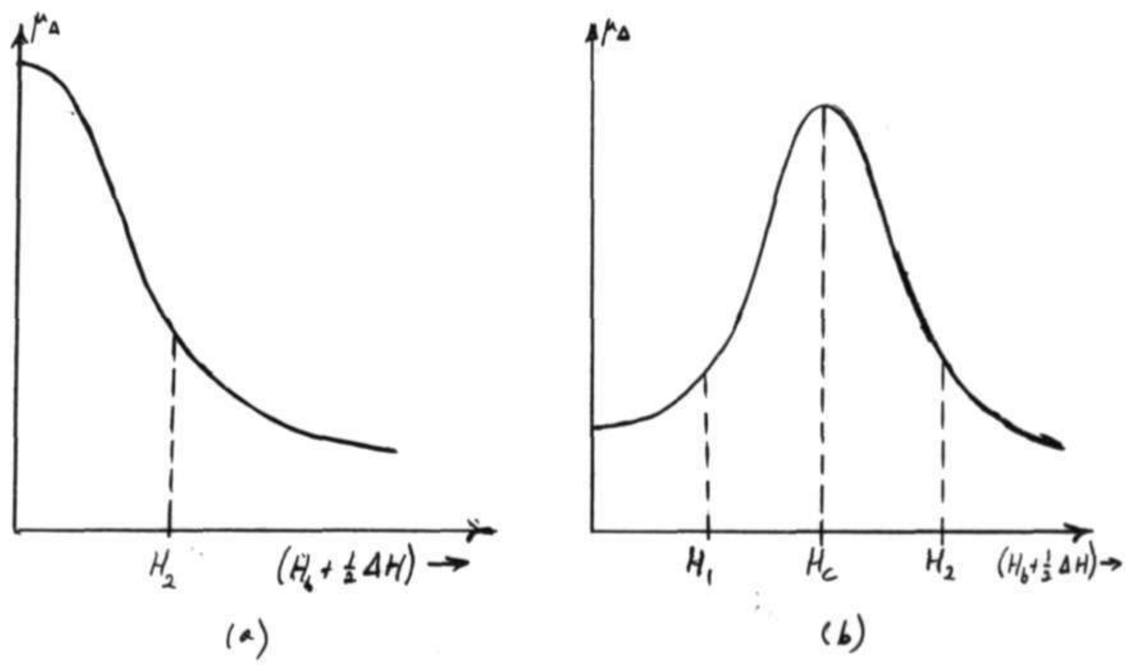

Figure 4

Schematic plot of incremental permeability vs. biasing field for (a) initial magnetization curve and (b) a major loop.

The values of μ_Δ with biasing field are indicated for the two cases in Fig. 4. The more square the B-H loop, the closer together are H_1 and H_2 and therefore the greater $(\Delta \mu_\Delta / \Delta H_b)$ max. Further, the lower the coercive force H_c, the higher the maximum incremental permeability, and therefore the greater $(\Delta \mu_\Delta / \Delta H_b)$ max. The two essential requirements for a large $\Delta \mu_\Delta / \Delta H_b$ are a square B-H loop and a low coercive force. Since the maximum incremental permeability is the initial permeability, the optimum case is for a material which is initially demagnetized. If this is not feasible for the application in mind, however, the other alternative is nearly as good.

C. Materials with Low Anisotropy

If a crystal has practically no anisotropy, the coercive force of a well-annealed sample will be small, and its B-H loop will be similar to that shown in Fig. 5. In the vicinity of $H_b = 0$ the atomic moments can rotate easily in a small a-c field ΔH, and the incremental permeability is large.

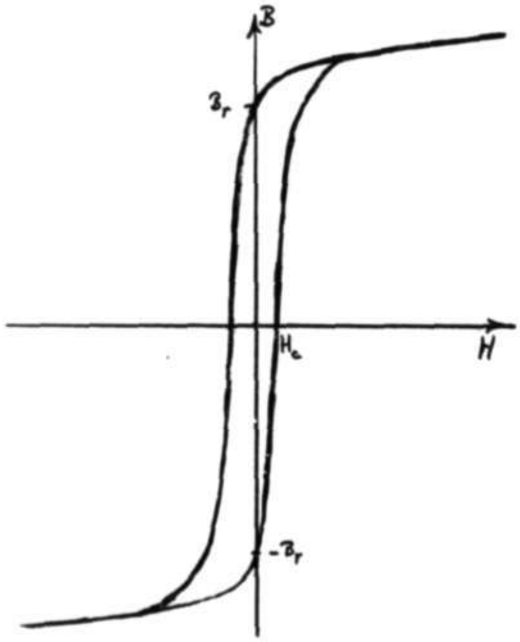

Figure 5. Typical B-H loop for a low-anisotropy material.

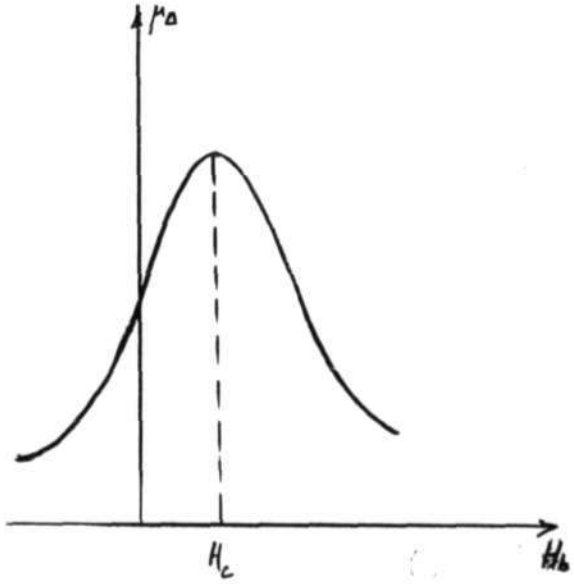

Figure 6.-Incremental permeability vs. biasing field for a low anisotropy material when curve is traced out by changing the field from $H_b = -\infty$ to $H_b = +\infty$

It has its maximum value at $H_b = H_c$ where the atomic moments have their largest component perpendicular to the a-c field. At values of $|H_b| \gg |\Delta H|$, however, the incremental permeability decreases since the atomic spins are still aligned by the field $|H_b| - |\Delta H|$. From Figure 6 it is apparent that the optimum operating point should be at $H_b = 0$, $B = +B_r$ for $\Delta H_b > 0$ and $H_b = 0$, $B = -B_r$ for $\Delta H_b < 0$.

IV. A FEW SUGGESTED MATERIALS

If a thin sheet of grain-oriented material or a metal with a square B-H loop is desired, ribbons of $\frac{1}{4}$-mil 4-79 Mo Permalloy are recommended. These have good squareness and coercivities of 0.01 to 0.05 oe. They can be obtained from Magnetics Inc. If the arrangement of Figure 7 is used for the application described in IIIB2, the magnetic coupling should be adequate and eddy-current losses should be minimized. If a ferrite with a square B-H loop and low coercive force is desired, it is recommended that some of the new materials being prepared by Frank Vinal of Group 63, Lincoln Laboratories, be tried. If a low anisotropy material is desired, a well-annealed sample of 70-30 Ni-Fe alloy should be applicable.

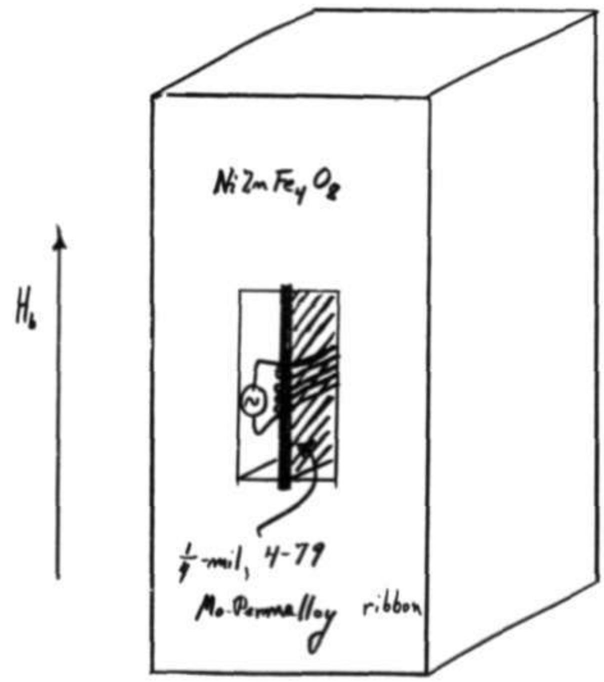

Figure 7

Possible arrangement for low-loss magnetic coupling with a metal tape.

Acknowledgment

This report is a summary and extension of some ideas which came up during a discussion with P. K. Baltzer and J. H. McCusker of Lincoln Laboratories and P.H. Haas of the Diamond Ordnance Fuze Laboratories.

Signed: John B. Goodenough
John B. Goodenough

Approved: DRB
David R. Brown

JBG/md

DISTRIBUTION LIST

All Staff Members, Group 63